

10 October 2012

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FINAL REPORT

Modification of the stratification and velocity profile within the straits and seas of the Indonesian Archipelago

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Award Number: N00014-10-1-0317

The gap in understanding basic ocean physics of the Indonesian seas is most acute in the northeastern seas: the Halmahera Sea, Maluku Sea, the Seram Sea and the northern Banda Sea (Spice Islands). Besides the monsoonal forcing there is an abundance of intraseasonal features of varied scales, derived from: the energetic Pacific western boundary currents that project into the region by way of the Mindanao and Halmahera Retroflexions (Eddies); localized winds blowing through the gaps between the islands composing the "Spice Island" configuration, inducing submesoscale clockwise and counterclockwise wind stress structures; strong tidal currents amidst the array of small seas and narrow passages. These factors make for a vigorous turbulent environment, one that is poorly understood, yet it is necessary to develop a quantitative grasp of the associated small scale ocean processes to properly model the regional circulation, and its role in the climate and marine ecosystems.

The objective of N00014-10-1-0317 was to develop and present this theme to our Indonesian colleagues, with the intention of developing a field activity in the Spice Island region, perhaps in stages, i.e. a pilot program to gather information for the design of a more extensive field expedition. A.L.Gordon and A.Ffield pursued this in lecture tours in Indonesia in July/August 2010; and by A.L.Gordon discussions with Indonesian colleagues in Jakarta in March 2012 and June 2012.

In 2010 we discussed an exploratory research cruise in the 2012 to 2013 period aboard an Indonesian research vessel, Baruna Jaya IV, into the Seram, Halmahera and Maluku Seas, the Spice Islands domain, to obtain an initial 'snap-shot' view of the stratification and circulation within these seas. While such a snapshot in this otherwise data void has merit in its own, it provides essential 'exploratory' information to compare to HYCOM model output and to build a more targeted observational, modeling program (and could contribute to ONR FY2012 MURI Topic #16 "Extended-Range Environment Prediction using low-dimensional dynamic modes"). In addition, we arranged, as part of

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the 2012 research cruise to recover, in coordination with Ariane Koch-Larrouy, the French IndoMix ADCP mooring at the northern sill of the Halmahera Sea.

A no funds extension for a 3rd year (2012) of this grant was granted to bridge the gap to possible new funding to cover field work and for continued discussion with Indonesian officials for continued cooperative research in Indonesian waters.

The 3rd year saw these activities: In March 2012, A.L.Gordon attended a CLIVAR Task team on the ITF, at Ancol, Indonesia. A program called GATEWAY was discussed with Indonesian and Korean colleagues. A proposal by A.L.Gordon and A.Thurnherr (both of Lamont-Doherty) and Jae-Hun Park [of KORDI] was submitted to NSF/OCE in August 2012, entitled "The Mindanao Current Variability". The objective was to investigate the tropical Pacific flow into the ITF.

The summary of the proposal:

The western boundary of the Pacific is not a 'wall' but rather a series of inter-island passages and marginal seas, a subset of which provide a connection to the Indian Ocean. There are many challenges, observational and modeling, in quantifying the relationships of the varied components of the Pacific's western boundary region and the associated meridional fluxes of heat and salt. One important piece of the puzzle concerns the Bifurcation of the North Equatorial Current (NEC) upon reaching the eastern coast of the Philippines. A component of the resultant flow heads north to feed into the developing Kuroshio; another heads south forming the Mindanao Current. The Mindanao Current is the focus of our proposed field program during which we plan to monitor meridional transport near 7°N over a 3-year period. South of Mindanao island the Mindanao Current forms a retroflexion (also referred to as an "Eddy" or "Dome"). Most of the retroflexion water curls back to the east into the North Equatorial Countercurrent (NECC), while some feeds the Indonesian throughflow (ITF). We propose to deploy an array of 7 Current-Pressure-recording Inverted Echo Sounders (CPIES) to monitor the Mindanao Current. The 3-year time series will record intraseasonal events, the seasonal cycle and reveal the interannual response of the Mindanao Current to ENSO and to meridional shifts of the NEC Bifurcation. The moorings will be deployed in spring 2014; data will be downloaded and failed instruments replaced in winter 2015/16, about 20 months after initial deployment to avoid the fall typhoon peak; and the moorings will be recovered in spring 2017. During all three cruises, full depth CTD/LADCP profiles of the hydrography and the three-dimensional velocity field will be collected. A total of 42 satellite tracked surface drifters will be deployed, 14 on each of the 3 cruises: half along the 7°N section and the remainder upstream of the CPIES array, to observe the trajectories of the Mindanao Current across the CPIES array and into the Mindanao Retroflexion. The drifter component of our proposal provides a direct link with TIPEX (Tropical Indo-Pacific water transport and ecosystem monitoring experiment) of Korea Institute of Ocean Science and Technology (KIOST), which includes a proposed spring 2014 deployment of mooring array of ADCP, CM, T/S sensors within the Mindanao Retroflexion and NEC measurement within the on-going POSEIDON project. Downstream ITF transport is monitored in the Makassar Strait (NOAA program) and at

the ITF primary export portals through Ombai Strait and Timor Passage. These are monitored as part of the Australian Integrated Marine Observing System.

In June 2012 A.L.Gordon presented a lecture at the Seminar on the Science of the Halmahera Sea, entitled: "Oceanography of the Indonesian Seas; the Challenge of the (spicy) Halmahera and Seram Seas ". This included the following topics:

Pacific Ocean Entry Portals:

- South China Sea via Luzon Strait to Karimata and Sibutu;
- Tropical Pacific via Mindanao & Halmahera Retroflections

Indian Ocean Exit Portals:

Sunda Archipelago passages:
Lombok, Ombai, Timor,
[Sunda Strait, Malacca Strait]

Interior Seas, the mix-master (outflow differs from inflow):

Makassar Strait: western boundary,
primary inflow pathway;
Eastern seas: Banda 'cyclonic gyre',
Seram/Halmahera/Maluku Seas puzzle

The June 2012 lecture included this material, which represented an expansion of the presentations in 2010:

The gap in understanding basic ocean physics of the Indonesian seas is most acute in the northeastern seas, Spice Island domain: the Halmahera Sea, Maluku Sea, the Seram Sea and the northern Banda Sea (Figure 1). These seas are exposed to the energetic Pacific western boundary currents rich in intraseasonal activity (Figure 2), that project into the region by way of the Mindanao and Halmahera [Eddies] Retroflections. The complex submarine topography coupled with the strong tidal action (Figure 2) and wind textured by the island topography lead to a vigorous turbulent environment, one that is poorly understood, yet it is necessary to develop a quantitative grasp of the associated small scale ocean processes to properly model the regional circulation, and its role in the climate and marine ecosystems

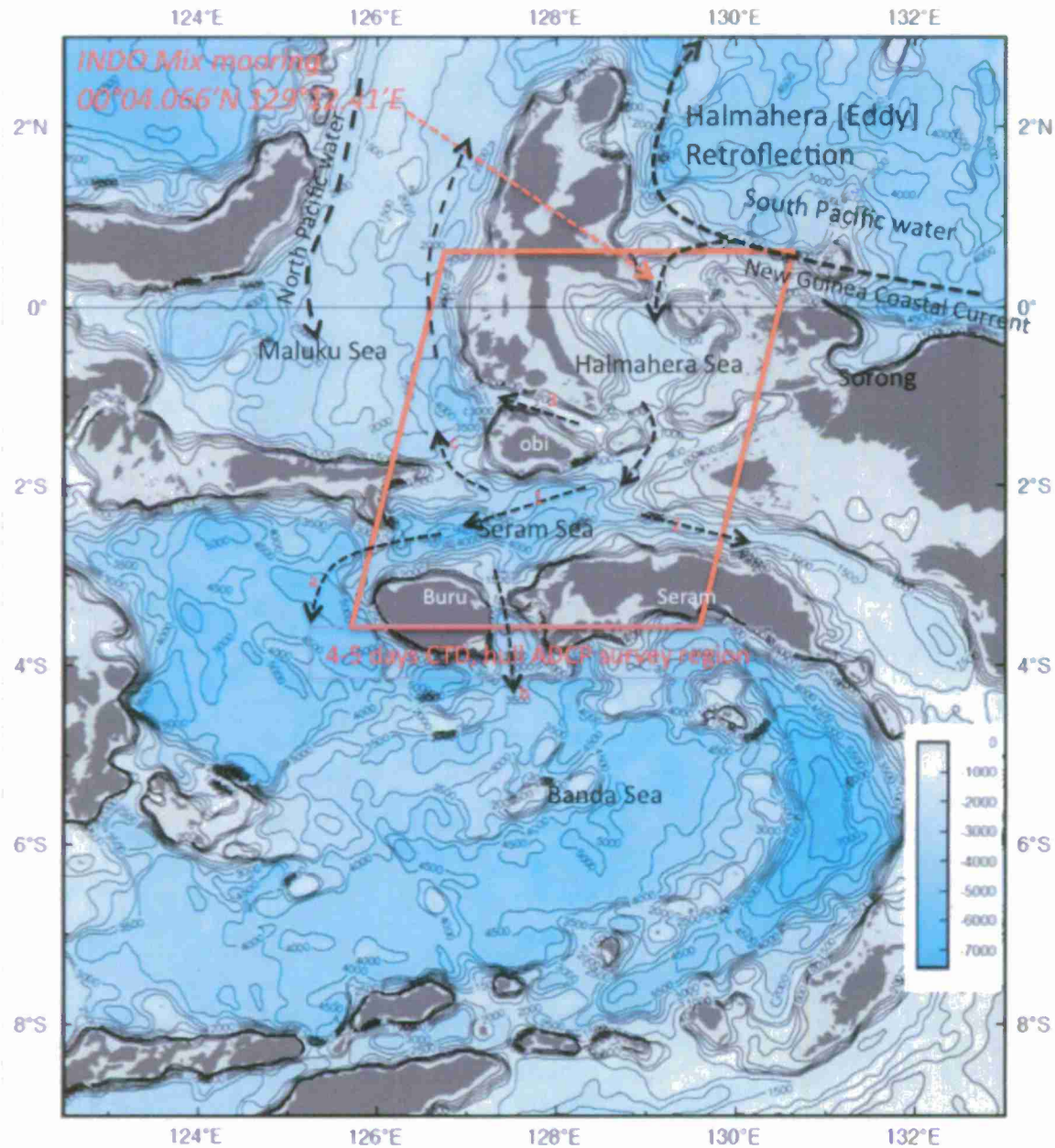
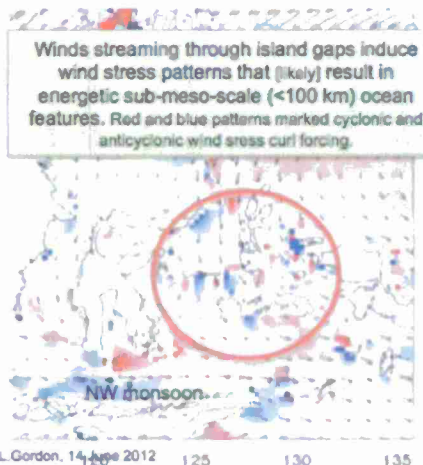
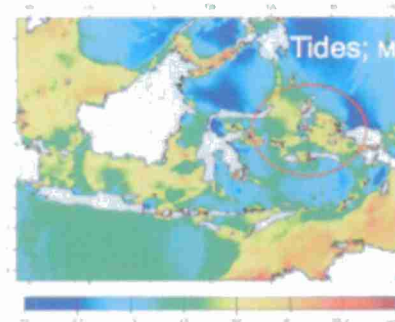
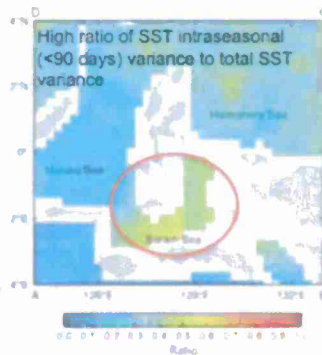


Figure 1. The Region. South Pacific water passes into the northern Halmahera Sea over the 580 m sill (Gordon et al. 2003; near the position of the 650 m deep French IndoMix mooring to be recovered by this proposed program), splitting off from the New Guinea Coastal Current, a component of the Halmahera Retroflexion ("Retroflexion" is more proper than "Eddy" often used to identify this feature). The southern exit is more complex and highly time variable (inference from HYCOM). Three paths are likely: 1: south of Obi, westward into the region of the western Seram Sea north of Buru, from which the flow may follow three paths (a,b,c); 2: eastward along the northern coast of Seram, into the eastern arc of the Indonesian Seas; 3: Within the narrow channel north of Obi towards the Maluku Sea. While Arlindo 1993/94 data (Ilahude and Gordon, 1996) suggests that the Maluku (North Pacific) and Halmahera (South Pacific) inflow mainly

returns to the Pacific in the eastern Maluku, with some leakage (La Nina?) into the Banda Sea around Buru Island is likely. It is also likely that some Halmahera Seas inflow may follow the eastern arc of the Indonesian seas to the Timor Passage and Indian Ocean.

HYCOM the surface currents in the Halmahera/Seram Seas display strong intraseasonal (<90 days) fluctuation, subject to periods of strong surface currents, 2-3 knot, probably extending through the thermocline. The model output frequently shows a zonally elongated circulation cell encompassing Seram Island. From March to October, it is likely to be counterclockwise; in the November to February, a clockwise circulation is more likely. However, there are fluctuations in strength and rotational sense on shorter, intraseasonal, time scales, at scales of weeks to months, defying a simple seasonal approach. The flow in the Halmahera group varies with season, but the path followed on water ejected southward from Halmahera into the Seram Sea varies seasonally but also at intraseasonal scales, with flow directed westward north and south of Obi island (Figure 1) or into the Seram Sea to enter into the circulation cell around Seram island. The Seram Sea is a 'traffic cop' directing the Pacific inflow into multiple possible exit passages. The energetic intraseasonal features are most likely imported from neighboring regions, e.g. the western Pacific, but may also be a response to the Madden-Julian Oscillations (MJO). The shift and change in wind strength associated with MJO may alter the wind stress curl field and induce some intraseasonal signal to the Spice Island region.



Monthly composite of phytoplankton concentration. The composites are computed from datasets during years of 2004-2008

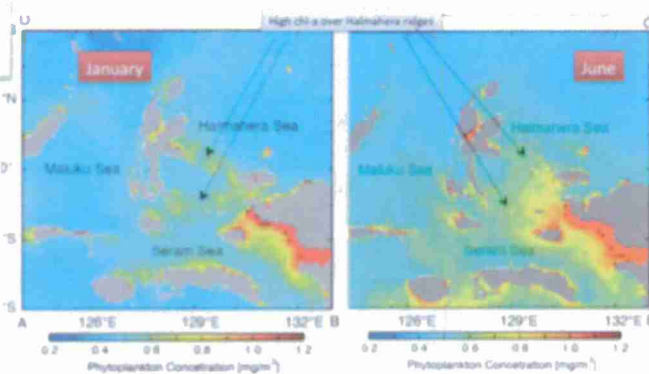


Figure 2. Ratio between the SST variance for intraseasonal timescales and the total SST variance over the maritime continent (left panel). Right panel demonstrates an expanded view of the ratio in the Spice Islands region. [Figure produced by Kandaga Pujiana]

ratio is computed using the following formula:
$$\text{Ratio} = \frac{\int_{T=20\text{-day}}^{T=90\text{-day}} \text{SST}^2(T) dT}{\int_{T=20\text{-day}}^{T=365\text{-day}} \text{SST}^2(T) dT}$$

Intraseasonal features are most intense in the Seram Sea, immediately south of the Halmahera Sea.

Maximum Barotropic current velocity of M2 tide [note the nonlinear color bar] tidal current. In the Spice Island region there is much tidal energy; the Spice Island region along with the region near Timor, display the highest M2 current speeds over deep water within the Indonesian Seas (Ray et al, 2005)

Monthly composite of phytoplankton concentration. The composites are computed from datasets during years 2004-2008. [Figure produced by Kandaga Pujiana]

The Marine Ecosystems of the Spice Islands is vibrant. Ocean Color from SeaWifs (Figure 2): There is a seasonal signal in the ocean color, with higher values in the Spice Island Seas in the SE monsoon (June-September) than in the NE monsoon (December-March). While high ocean color is typical of the near coastal zones, there is persistent color over the northern and southern ridges defining the Halmahera Sea. These we propose are sustained by high vertical fluxes induced by high Kz.

The Spice Island domain lies at the center of the Coral Triangle (Figure 3; <http://www.coraltrianglecenter.org/en/page/about-ctc>)

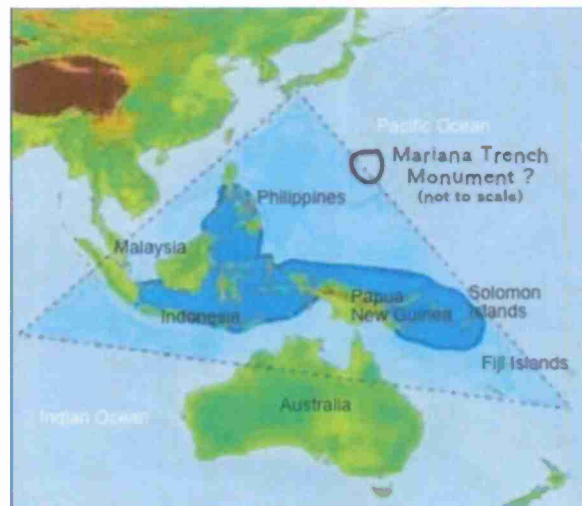


Figure 3. The Coral Triangle is a region covering over 6 million square kilometers

that holds the greatest number of corals, sponges, crustaceans, mollusks and fish on this planet. There are over 600 types of coral, 3000 species of fish, sea turtles, whales, and dolphins. It is now known as the global centre for marine diversity.

The broader research questions to be addressed are: How does the stratification, velocity/transport respond to remote and local forcing? What are the dominant physical and dynamical balances that characterize the flow & mixing at different locations and scales? How well do models simulate the observed characteristics?

The justification of the program is the premise that: improved understanding of the ocean processes within the northeastern seas of Indonesia, keyed to the complex geography and intraseasonal ocean/atmosphere activity, will provide the basis of improved high resolution ocean modeling with applications to such areas as understanding of the nutrient fluxes and larvae trajectories, and associated food chain structures that will allow for informed management of marine living resources: e.g. fisheries and coral reefs, for food and recreation. There would be improved prediction of pollution spreading and improved understanding of the flux of carbon dioxide between ocean and atmosphere (question: are the Indonesian seas a source or sink of atmospheric CO₂?). The research will lead to improved ocean and climate modeling for better prediction of hydrological changes affecting Indonesia.

Conclusion: Unfortunately, the exploratory cruise envisioned for 2012 did not take place. This was due to lack of funding from ONR for that activity. Attempts to bootleg the collection of data in the Spice Island region as part of another program [deployment of a NOAA funded ADCP mooring in Makassar Strait], did not work out. On a positive note: N00014-10-1-0317 did lead to increased awareness of the interesting, but not yet fully resolved oceanography of the Halmahera, Maluku, and Seram Seas and of the northern Banda Sea. Maybe, eventually, we can learn more about their complex environment and achieve effective modeling of the governing processes.